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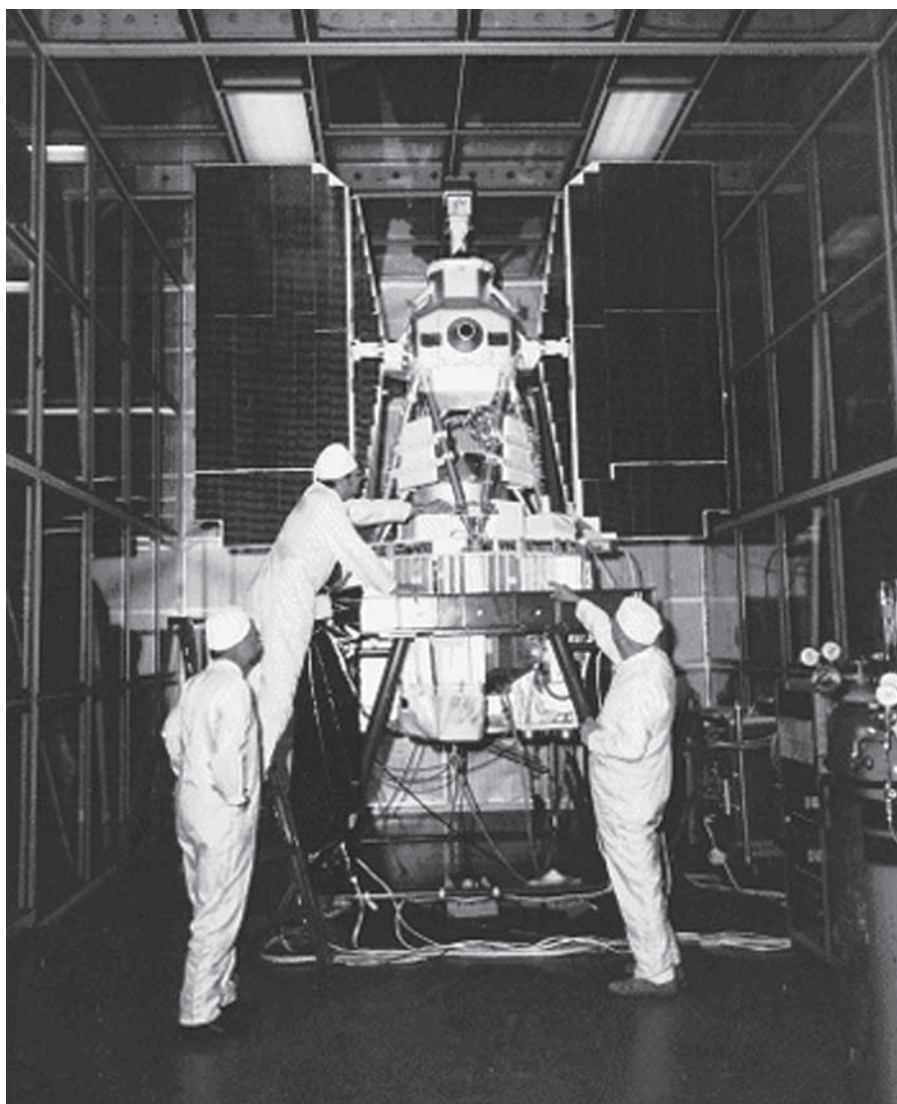
ASLO

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Limnology and Oceanography



ABOUT THE COVER IMAGE

Read about the origins of today's satellite-based oceanography in James Acker's article, which is part of this issue's special feature on ocean color.



Nimbus Satellite. Image courtesy of NASA, Total Ozone Mapping Spectrometer (TOMS) photographic archive.

OCEAN COLOR: THE LEGACIES OF ANDRE MOREL AND CHARLES YENTSCH

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HOW TWO SIDES OF THE ATLANTIC CONTRIBUTED TO UNDERSTANDING OF THE GLOBAL OCEANS: CHARLES YENTSCH AND ANDRE MOREL

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INTRODUCTION

In a few short days in September of this year, the ocean color/ocean optics community lost two of the founding members of its Hall of Fame—Charles Yentsch and Andre Morel. Yentsch passed away at the age of 85 on September 19, and Morel passed away on September 23 at the age of 79.

It might sound cliché to say that someone was instrumental to the advance of science in a particular field, but in the case of Yentsch and Morel and ocean color instrumentation, such an assessment would likely be accurate. Each man's career complimented that of the other; Yentsch was one of the first to make measurements of the light field of the ocean from altitude and to advocate an instrument in space that could observe the spectrum of ocean radiance; Morel's theoretical underpinnings

established a firm foundation for the measurements such an instrument could make, allowing their successful interpretation.

BEGINNINGS

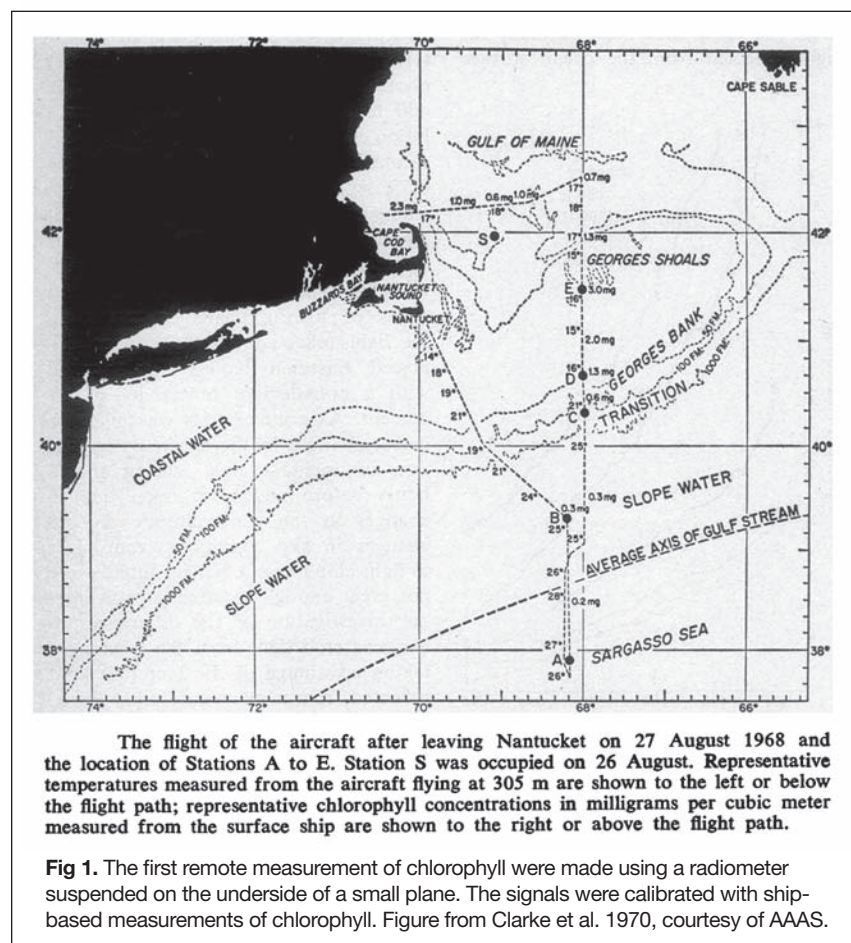
Intriguingly, both men followed somewhat similar paths to the sea. Yentsch first immersed himself in the marine realm as a U.S. Navy diver, while Morel was an officer and also a diving instructor in the French Navy from 1958–1961, after receiving an engineering degree from the Ecole Supérieure de Physique et Chimie in Paris. Both men pursued graduate degrees—Yentsch received a masters degree from Florida State University with research on barnacles (his interest likely piqued with first-hand experience on the underside of ship hulls), while Morel received two advanced degrees, one from the Faculté des Sciences de Paris in 1967, and the second from the Université Pierre et Marie Curie in Paris. His thesis topics for both were concerned with the interaction of light and water. Yentsch began a doctoral program at the University of Washington, but before he got very far, he was invited to Woods Hole by John Ryther in 1956. Ryther and Yentsch published their first paper on fluorescence measurements of chlorophyll and phaeophytin in 1959.

In 1965, Yentsch's paper, "Distribution of chlorophyll and phaeophytin in the open ocean," described how the color of the ocean might vary due to differing concentrations of chlorophyll and accessory pigments, forming the basic idea for observing ocean color to perceive biological activity. The necessity to prove that variations in color could be observed from altitude led to

the first attempts to fly a radiometer on a plane, likely in the summer of 1967, which was piloted by Gifford Ewing. Dick Barber happened to be on hand when the first flight results were examined by Yentsch and Ewing, definitely showing absorption by something containing chlorophyll—which David Menzel jibed was "only seaweed" (in this case, *Fucus* on the rocks of Cuttyhunk Island). Yentsch was part of the research group that made the first published suggestion (in a 1970 paper) that ocean color variability could be observed remotely (Fig. 1), based on low altitude flights of a spectroradiometer over the ocean surface (Clarke et al. 1970).

1970 also marked the research cruise of the Scientific Committee for Ocean Research (SCOR) Working Group 15, which was tasked to examine the "photosynthetic radiant activity of the sea." Andre Morel was on this cruise, which had intended to examine the prolific Peru Upwelling Zone, but was forced to stay in gin-clear, low-productivity waters well offshore due to international treaty concerns.

Morel and Yentsch paralleled each other's careers in the 1970s, as Morel published regularly, including an important chapter in "Optical aspects of oceanography," edited by Nils Jerlov and E. Steeman Nielsen in 1974, entitled "Optical properties of pure water and pure seawater."



As more sophisticated instruments were developed and deployed at sea, some of which Morel collaborated on with members of the Scripps VisLab, NASA hatched the idea of putting an ocean color instrument on the Nimbus satellite series. The early airborne radiometer measurements made by oceanographers had been followed, logically, by a NASA aircraft campaign, led by Warren Hovis, who became the leader of the proposal team for the Coastal Zone Color Scanner (CZCS, Fig. 2). The CZCS fabrication commenced in 1973, and the instrument required a science team under NASA's radical new way of doing things for Nimbus 7 (cover image), in which a scientific team was an integral part of the instrument's planning and eventual orbital operation. The teams, called Nimbus Experiment Teams (NET), were selected by the instrument scientist. Yentsch was one of the scientists selected by Hovis for the CZCS NET. As this team was grappling with the problems of how to actually process the data from the instrument, Morel and his collaborator Louis Prieur published a seminal paper in 1977 that would be referenced subsequently in numerous papers utilizing CZCS data, "Analysis of variations in ocean color." This paper, which defined the optical distinction between Case I (clear) and Case II (turbid) ocean waters, and the subsequent successful launch and pioneering mission of the CZCS, linked up the careers of Morel and Yentsch permanently.

Morel actually hosted one meeting of the CZCS NET at his Villefranche-sur-Mer laboratory in May of 1980, a meeting perhaps most notable for what followed directly after, the COSPAR/SCOR/IUCRM Symposium on Oceanography from Space, held in Venice, Italy on May 26–30, 1980. This meeting marked the first release of scientific results from the CZCS.

Data from the CZCS enabled numerous publications linking ocean biology and ocean optics to ocean color data from space. Morel and his colleagues authored many papers utilizing the

data and expanding the theory of ocean color; with more data in hand, Morel and Howard Gordon of the CZCS NET published "Remote assessment of ocean color for interpretation of satellite visible imagery—a review" in 1983.

Yentsch, while continuing to be an active member of the ocean color community, also found another line of "work," which was founding oceanographic laboratories. These laboratories were the Nova University Oceanographic Center in Fort Lauderdale, the University of Massachusetts Marine Station, and ultimately, in July of 1974, Charlie and his wife Clarice founded the Bigelow Laboratory for Ocean Sciences in West Boothbay Harbor, Maine. Although his active research career has precluded his acquisition of a research doctoral degree, he received an honorary doctorate in 1985 from Long Island University. He subsequently received several awards, including the Lifetime Achievement Award from the American Association of Limnology and Oceanography (ASLO) and the Jerlov Award. Through both his scientific research and the guidance he gave to the oceanographic laboratories he led, particularly to the numerous scientists who worked and trained at the Bigelow Laboratory, Yentsch was both a valued colleague and inspirational leader.

Morel also needed a shelf for oceanographic awards; he received the Eurosense Award of the Remote Sensing Society (UK), the Prix Binoux de l'Académie des Sciences, the Jerlov Award, the Médaille Albert 1er, Prince de Monaco, the Manley-Bendall Medal of the Oceanographic Institute in 2003, and also the Redfield Award for Lifetime Achievement from ASLO. Morel's prolific publishing record with numerous colleagues, through the final years of his life, indicates a remarkable scientific career.

YENTSCH, MOREL AND THE ADVANCEMENT OF OCEAN COLOR SCIENCE

When the first CZCS images were received and analyzed, Yentsch humbly assessed them as indicating that the system had worked as he expected, validating what he called a "simplified" view of what the primary influences on the ocean optical environment would be. Since he had become very familiar with Georges Bank, he was quite pleased to see that the Georges Bank system, viewed from space (Fig. 3), looked just about as he had envisioned it would. Despite this reassurance, Dick Barber noted that the first images from the CZCS demolished the commonly held misperception of alongshore continuity—"jets" and "squirts" and variability in current meandering indicated that the ocean was a much more complex place than point sampling had led many to believe.

Thus, even before the mission had logged a year in space, Yentsch was already looking toward the future, marking his position as an energetic advocate of space-based remote sensing of the oceans. Yentsch noted that since CZCS had already established that the primary factor which determined the color of the ocean was its level of biological productivity, ocean color remote sensing should become a "significant element" of NASA's oceanographic remote sensing portfolio, because this method of remote sensing could allow estimates of global ocean productivity.

Morel, meanwhile, was attacking the problem of ocean color interpretation from the underside. His published works

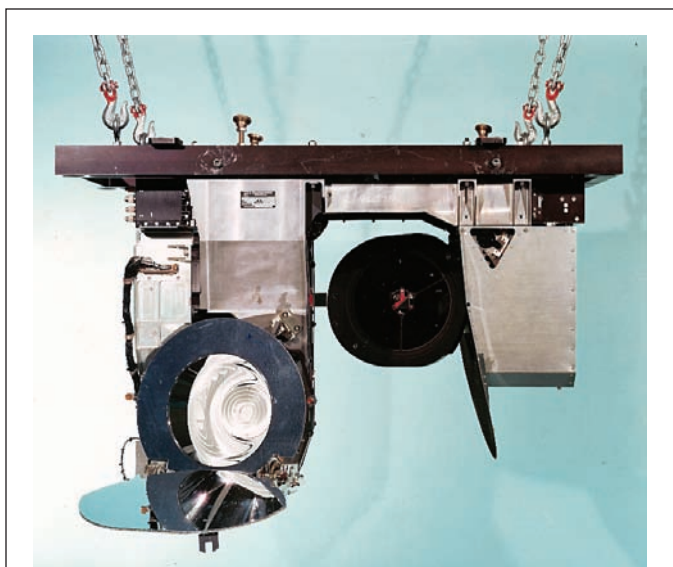


Fig. 2. Completed protoflight model of the Coastal Zone Color Scanner (CZCS), at Ball Brothers prior to Nimbus 7 integration. A second CZCS, which never made it to orbit, is still in storage at Goddard Space Flight Center. Image courtesy of NASA/Ball Aerospace, Inc.

in the early 1980s focused brightly on the theoretical aspects of ocean optics with relevance to remote sensing; he published on light absorption, phytoplankton optical efficiency, scattering of light by chlorophyll-containing cells, and the inherent optical properties of phytoplankton cells, down to the minute scale of picoplankton.

There is a definite coherence to the understanding of ocean optics and remote sensing in which Yentsch and Morel were primary participants. Yentsch defined the major factors that would influence the detection of the ocean color signal in space, and provided that analysis of the data was sufficiently accurate, this analysis would lead to better quantification of the biological characteristics of ocean waters. Morel's expansion of the ocean optical model, which addressed the optical characteristics of its biological entities, enabled an improved quantification of the factors contributing to the signal. Interaction of the ocean optical environment and the atmospheric optical environment created the signal that the satellite instrument actually detected; only with a thorough understanding of both was it possible to evaluate whether the subtraction of the atmospheric component (which in fact dominates the signal) was providing reasonably accurate numbers for the oceanic component. Morel eventually addressed the CZCS directly in 1987 with Annick Bricaud in "Atmospheric corrections and interpretation of marine radiances in CZCS imagery: use of a reflectance model." He continued into the 1990s to examine various topics in ocean optics, occasionally dabbling in atmospheric correction as well.

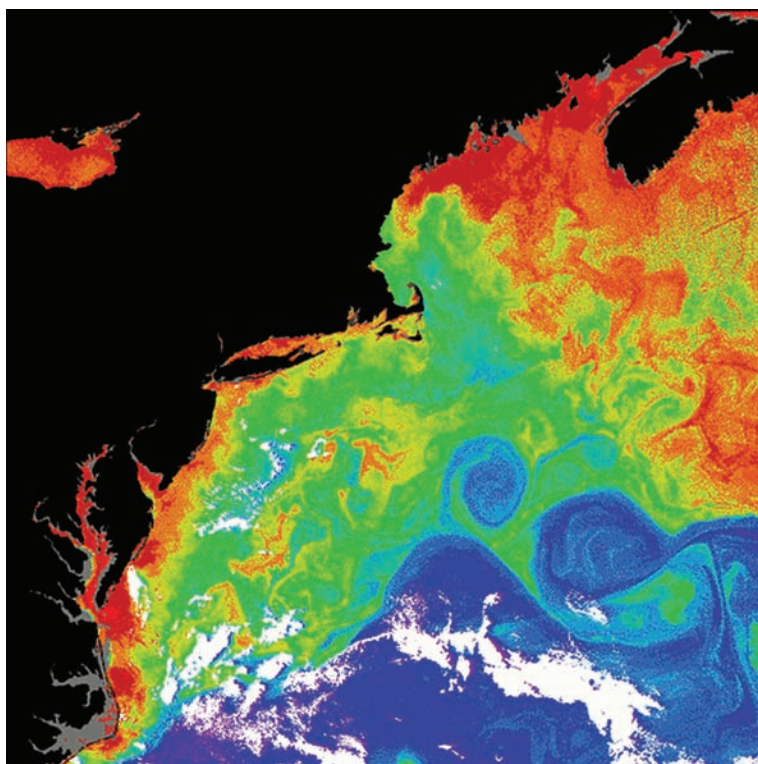


Fig. 3. Coastal Zone Color Scanner image of the Mid-Atlantic Bight, distinctly showing Gulf Stream eddies. This image was published in the December 1981 issue of *National Geographic*. Image courtesy of Howard Gordon.

SEAWIFS

The late 1980s were distinguished in the ocean color community by the frustrating inability of NASA and its collaborators to build and then launch a follow-on sensor to the CZCS, despite the overwhelming success of the CZCS and the clear recognition of the vital nature of remotely-sensed ocean color data for improved understanding of the global carbon cycle. Indeed, the travails of this pursuit could fill a long chapter in a book (and a book with such a chapter is actually nearing publication). Yentsch had participated in furthering this process by filling an entire room at the Bigelow Laboratory with CZCS data tapes, and then luring researchers to West Boothbay to analyze them, resulting in even more publications that demonstrated the usefulness of the data. Thus, when the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, Fig. 4) mission finally found a partner in Orbital Sciences Inc. for its unique and slightly unwieldy public-private partnership, Morel and Yentsch were logically selected as members of the large SeaWiFS science team (Hooker et al. 1993).

While SeaWiFS was delayed for four long years, finally reaching space in 1997, Morel continued to publish several papers a year in the ocean optics field. The launch and operation of SeaWiFS finally placed a dedicated ocean color sensor in space, providing global, near-continuous observations of the world ocean—and finally enabling the use of global models integrating ocean optics to generate estimates of chlorophyll concentration and eventually primary productivity. The CZCS had shared power on Nimbus 7 and had therefore only provided

intermittent coverage of ocean waters, primarily coastal, as its name indicated. Only in the last months of the CZCS mission did nearly full-time operation provide the opportunity to create a nearly global single image of ocean chlorophyll concentrations. SeaWiFS accomplished the same thing in approximately the first month of its full-time operational status (Fig. 5).

The success of the SeaWiFS mission and the subsequent success of the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite, launched in 2002 (MODIS-Terra, launched late in 1999, had a few problems that made its data less accurate than required for accurate ocean color calculations) was further validation of the ground-floor work that Yentsch and Morel had conducted. SeaWiFS launched at the opportune time to observe both a large El Niño and a subsequent large La Niña event, with the “downside” that it was only in its third year of operation that it actually observed the Pacific Ocean in a “normal” physical and biological state. Although it took quite a bit of computational effort, this allowed Michael Behrenfeld and his cast of co-authors in 2001 to calculate how much less carbon was produced globally when El Niño ruled the waves, and how much more carbon was produced when the cool La Niña conditions enhanced phytoplankton productivity. This paper confirmed Yentsch's prescient statement from 1979 that remote sensing of ocean

color from space could indeed allow estimation of global primary productivity.

One of the continuing problems with ocean color remote sensing is that of data validation—collecting sea-truth data to compare to the data acquired by the satellite, to determine how accurate the data from the satellite really is. This particular problem occupied much of Morel's effort in the first decade of the 21st century, as he and his colleagues examined the use of instruments on floats (such as a Bio-Argo float) and moorings (the BOUSOLE platform in the Mediterranean Sea) to collect data useful for validation. He continued to publish ocean optics papers, and also participated in papers examining the data from Joint Global Ocean Flux Study (JGOFS) time-series stations. While Yentsch was enjoying his time in Maine as an emeritus director of Bigelow, he was still working with colleagues on ocean optical problems, notably Barney Balch (who credited Yentsch with spurring his interest in oceanography at the young age of 14). Balch and Yentsch began publishing together in 1983, and Balch continued working on topics in ocean color at Bigelow, in particular the problem of quantifying calcifying plankton species (coccolithophores) with remote sensing.

It is a testament to the lives and minds of Charlie Yentsch and Andre Morel that they continued working with, and inspiring, numerous oceanographic scientists through the final years of their lives. The history of ocean color is rife with references to their work, and this only partially characterizes the full spectrum of their contributions to the field. Both of these brilliant men were constantly looking for the next question to answer, the next problem to address. They participated on instrument proposals, instrument teams, review panels, steering committees, scientific panels, and also were directly involved in the science with at-sea work under the satellite instruments that they had helped place in orbit. They were both present at the nascent beginnings of this branch of science, established its viability, and lived to see its im-

pressive maturity, providing daily views and daunting insight into the fundamental workings of the ocean's biological processes.

ACKNOWLEDGMENTS

"The Color of the Atmosphere with the Ocean Below: The Difficult Path to Successful Biological Remote Sensing of the Global Ocean," by James Acker is slated for publication by NASA in 2013. Numerous oceanographic scientists contributed directly to this history via personal and phone interviews and information sent via email. In particular, Charles Yentsch, Andre Morel, Richard Barber, Janet Campbell, Howard Gordon, and David Antoine provided information that appears in this article. The author would like to acknowledge funding for the history project, which was provided by NASA's Science and History divisions. The NASA SeaWiFS Project (now the Ocean Biology Processing Group) was the source of several images in this article and information on the CZCS, SeaWiFS, and MODIS missions.

RESOURCES

http://www.obs-vlfr.fr/LOV/OMT/personnes/z_more_an/morel.php

<http://www.bigelow.org/about-bigelow-laboratory/history/charles-s-yentsch>

<http://www.whoi.edu/main/obituaries?tid=3622&cid=151190>

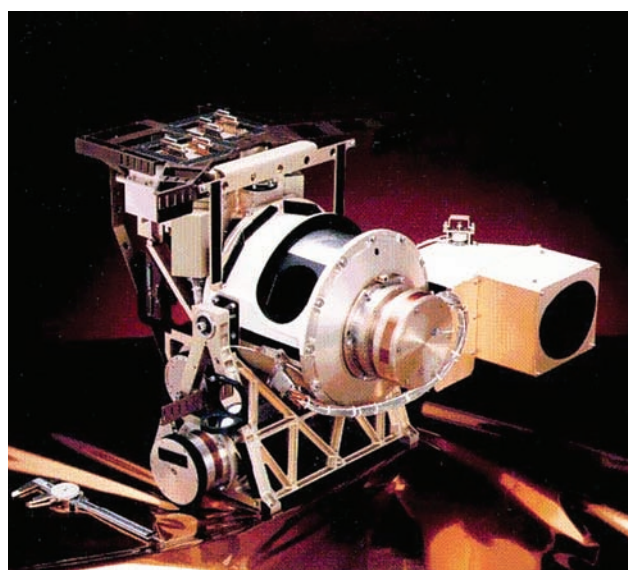


Fig. 4. Image of the finished Sea-viewing Wide Field-of-view Sensor, which provided the first nearly continuous ocean color data set. Image courtesy of the NASA Ocean Biology Processing Group.

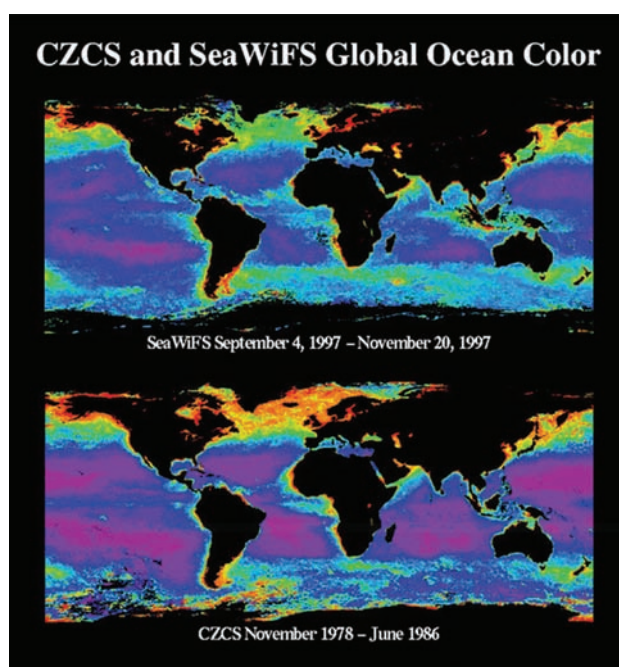


Fig. 5. Comparison of the first SeaWiFS global ocean color image, assembled using data acquired from September 4, 1997 through November 20, 1997, to the single CZCS global ocean color image, assembled using data acquired over the course of the entire 8-year observational mission. Despite the gap between the missions and the difference in technology, the two images showed remarkably similar patterns of ocean color. One significant difference was the Equatorial Pacific upwelling zone, which was nearly absent in the SeaWiFS image due to the strong 1997-1998 El Niño event. Image courtesy NASA Ocean Biology Processing Group.

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OBITUARY: CHARLES S. YENTSCH, 1927–2012

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Dr. Charles S. Yentsch, pioneer of the field of ocean optics and ocean color remote sensing, died on 19 September 2012 at the age of 85. Charlie was part of the emergence of academic oceanography that took place in the U.S. after World War II, a period when scientists from a multitude of disciplines gathered at a handful of oceanographic institutions to pursue interdisciplinary studies of the oceans. His first major exposure to the oceans came while serving as a fire fighting instructor and salvage diver in the U. S. Navy. Charlie long ago noted that his first view underwater through a face mask motivated his life-long interest in the complex interplay of light and life in the sea. After the Navy, Charlie returned to attend the University of Louisville (in his home state of Kentucky), from which he graduated in 1950. Charlie followed this with graduate studies on barnacles and light at Florida State University where he earned a M.S. degree in 1953. In 1956, Charlie left his Ph.D. program at the University of Washington to become a research associate at the Woods Hole Oceanographic Institution at the invitation of Francis Richards. There he began his ground-breaking work

with phytoplankton pigments, a topic which became both the foundation and the common thread of a long and distinguished career as an innovator, researcher, scientific leader, laboratory founder and director.

Charlie was involved in the founding of three oceanographic laboratories during his career. In 1968 Charlie left WHOI to join Bill Richardson in the formation of the Oceanographic Center at Nova University, Fort Lauderdale, FL (now known as Nova Southeastern University Oceanographic Center). In 1970 he returned to New England to start the University of Massachusetts Marine Station (Gloucester, MA). A state moratorium on hiring in 1974 prompted Charlie to begin negotiating with the Maine Marine Commissioner and Governor, to occupy lab space vacated by the former National Marine Fisheries Service research station in West Boothbay Harbor, ME. He moved lab personnel, equipment and a small research vessel to Maine in June, 1974 and he and his wife, Clarice M. Yentsch, co-founded the Bigelow Laboratory for Ocean Sciences. In 1985, following three decades of work in oceanography, Charlie accepted a Ph.D. *Honoris Causa* from Long Island University. Although Charlie never felt that a Ph.D. was necessary to do good work, he was honored by the recognition. The American Association of Limnology and Oceanography (ASLO) presented Charlie with their prestigious Lifetime Achievement Award in 1999. In 2010, The Oceanographic Society bestowed the honor of the Nils Gunnar Jerlov Award and also named him a Fellow.



Charles Yentsch. Photo by Bob Mitchell.